Future Petroleum Producing Capacity of he United States

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*discussion of the nature of certain pe-
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r future supply*

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FUTURE PETROLEUM PRODUCING CAPACITY OF THE UNITED STATES

By A. D. Zapp

ABSTRACT

Prediction of future petroleum producing capacity should be based on the statistical record of the past, interpreted in the light of the known trends and circumstances that are not amenable to statistical expression. For a dynamic industry such as the petroleum industry, the most recent statistical record should be the most meaningful as to the future.

Recent published predictions of future producing capacity of the United States have been based primarily on either (a) the yearly estimates of proved reserves prepared by committees of the American Petroleum Institute and the American Gas Association, or (b) estimates of the total amount of ultimately recoverable petroleum, including the undiscovered quantity. These two types of estimates have been carefully examined so that the suitability of each as a basis for prediction could be appraised.

Estimates of proved reserves for recently discovered pools are, by their nature, subject to extensive revision in future years, and the historical record shows that such revisions have been almost invariably upward and that the increases have been of very considerable magnitude. The rate of development of a new supply of crude oil in the United States as suggested by recent proved-reserve estimates was found to be ultraconservative when examined in the light of the recent rate of increase in producing capacity, the decline-curve principle, and the major historical trends that affect the ratio of producible reserves to producing capacity. Accordingly, the statistics of proved-reserve estimates are not considered a suitable basis for predicting future producing capacity.

Ultimate "reserves" of petroleum consist of (a) the quantity produced plus the quantity yet to be produced from known pools, and (b) the economically recoverable quantity not yet discovered. History has shown that pre-1950 estimates of the ultimate "reserves" of the United States have already proved unreliable. Past production is measurable, but the amount yet to be produced from known pools is very uncertain because of the limitations of methods of estimating producible reserves, including unpredictability of the quantitative effect of technological progress. Estimation of undiscovered petroleum introduces further, and considerably greater, uncertainties. Only a relatively small proportion of geologically favorable rocks have been explored so far; the full

range of geologic settings of petroleum occurrence is probably not yet known; and present information is inadequate for quantitatively predicting the incidence of known favorable geologic settings in the unexplored rocks. Accordingly, it is concluded that it is not yet possible to predict ultimate "reserves reliably." But from consideration of the large volume of geologically favorable rocks yet to be explored, and the recent record of success in exploring geologically similar rocks, it is concluded that the quantity of undiscovered petroleum will not constitute a limiting factor on producing capacity in the next 10–20 years, at least, and probably for a much longer time.

From study of the nature and probable accuracy of the various types of quantitative data and estimates that might be used as a basis for prediction, it is concluded that the recent rate of growth in producing capacity itself is the most realistic basis. Producing capacity consists of the current rate of production, which is measurable, and the reserve producing capacity, which is virtually the amount by which production is curtailed to prevent overproduction with respect to market demand. The reserve producing capacity is an estimate, but is not subject to much error. Thus, estimates of producing capacity are intrinsically more accurate than estimates of either proved or ultimate "reserves"; moreover, by their nature, estimates of producing capacity are sensitive to recent trends and are verifiable on a short-term basis.

From near the end of World War II, when crude-oil wells in the United States were producing virtually at a capacity rate of approximately 4.7 million barrels daily, crude-oil producing capacity steadily increased to a level of about 9.9 million barrels daily at the beginning of 1957, according to a series of estimates based on surveys sponsored by the National Petroleum Council and the Petroleum Administration for Defense. This increase in producing capacity was principally due to the high and increasing rate of completion of new crude-oil wells. The relatively high capacity of these younger wells more than offset the normal slow decline in capacity of older wells. The increasing number of new oil wells was in turn the result of a great expansion in total number of wells drilled yearly—from about 25,000 at the beginning of the period to a peak of more than 57,000 in 1956—and maintenance of a consistent success ratio through extensive and increasing reliance on technical advice in locating and testing wells. Widening application of engineering advances, which tend to arrest decline in productivity both of old and new wells, and to rejuvenate some old wells, has also been an important factor.

If demand for domestically produced crude oil during the next 10–20 years justifies an expansion in drilling comparable to the expansion during the post-World War II period, an increase in producing capacity comparable to that of the recent past may be expected.

Past estimates of producing capacity for natural gas and natural gas liquids comparable to those for crude oil are not available to serve as a basis for prediction. These commodities are genetically associated with crude oil, however, and certain inferences as to future capacity to produce may be drawn from presently known quantitative relations to crude oil. From present knowledge of underground quantities and rates of extractability, it is evident that the capacity of existing wells to produce these commodities (without regard to pipeline or processing-plant capacity) is greater, relative to current production rates, than for crude oil. This will probably continue to be so for many years to come, for discovery of greater relative quantities of natural gas and natural gas liquids may be confidently expected with increasing average depth of exploration in the future.

INTRODUCTION

Any forecast of the future petroleum producing capacity of the United States obviously must be based on available measurements or quantitative estimates pertaining to petroleum, and there are several possible approaches to the problem, depending on which set of measurements or estimates is chosen as fundamental. Recent published predictions as to the future producing capacity of the United States have been based primarily on either the yearly estimates of proved reserves prepared by committees of the American Petroleum Institute and the American Gas Association or estimates of the total amount of ultimately recoverable petroleum, including the undiscovered quantity. A third possible basis for prediction is the recent record of increase in producing capacity, as shown by a series of recent surveys sponsored by the National Petroleum Council and the Petroleum Administration for Defense. Careful consideration was given to the nature and intrinsic accuracy of each type of data or estimate and the historical trends affecting them. From this study, it was concluded that the recent record of development of producing capacity is the most meaningful as to what may be expected in the foreseeable future. The reasoning that led to this choice is summarized in this paper.

The study was concerned entirely with domestic sources of fluid petroleum from natural subsurface reservoirs; supplemental sources such as oil shale were not included. A basic assumption in the study was that economic incentive to discover and produce petroleum in the future will continue comparable to that since World War II.

This summary is based in part on a staff study in which many members of the Geological Survey participated. Also, the author gratefully acknowledges many helpful suggestions from those who critically reviewed the manuscript.

RATE OF PRODUCTION AND PRODUCING CAPACITY

Rate of production is, of course, the rate at which petroleum is brought to the surface; producing capacity is the maximum rate of production possible under existing production practice. As discussed below (p. H–6), historical changes in general production practice have somewhat changed the meaning of the term "producing capacity."

Rate of production and producing capacity are commonly expressed as barrels per day for crude oil and as thousands of cubic feet (MCF) per day for natural gas. The units of volume are those under standard conditions of temperature and pressure at the earth's surface. In moving from the higher pressures in subsurface reservoirs to the lower pressures at the earth's surface, crude oil generally shrinks in volume because of loss of dissolved gas, whereas natural gas expands. Pressure increases with depth—consequently, the magnitude of these volumetric effects increases.

Production rates of individual wells or groups of wells are directly measurable by means of mechanical gauges inserted into gathering flow lines, or by the use of calibrated storage tanks for a measured period of time. However, the usual statistical data in terms of barrels daily or thousands of cubic feet daily represent *average* rates, derived by dividing monthly or yearly total production by the number of days in the month or year. Many oil wells in the United States are allowed to produce during only a certain number of days each month; so the statistical *average* rate of production is lower than the actual rate when the wells are continuously producing.

DECLINE CURVES

Experience with hundreds of thousands of wells has shown that the rate of production of an individual oil well, if continuously produced at the maximum possible rate and without change in production practice, declines steadily with time. A plot of the rate of production against time is called a decline curve. An example of one common type of decline curve—the "constant percentage (semilog, exponential)" curve—is shown, plotted on regular coordinate paper, in figure 1*A*. In this particular type of decline, the production rate at the end of each successive equal period of producing time is a fixed percentage of the rate at the end of the preceding period; a straight line results when the rate of production is plotted against cumulative production on regular coordinate paper (fig. 1*B*). Individual decline curves vary considerably in shape,[1] but virtually all are roughly similar in that they on regular coordinate paper are convex toward the origin when rate of production is plotted against time, as in figure 1*A*. Artificial stimulation of production by any of numerous present-day methods may rejuvenate a well and start a second cycle of decline. The rate of production eventually declines to a level too low for profitable operation and the well is abandoned. As stated by Ball (1940, p. 143), "No one can understand the oil business who has not grasped the universality of the decline curve * * *."

EFFECT OF CONSERVATION

Before about 1930 the petroleum industry attempted to recover oil at the maximum possible immediate rate. When a new field was found it was literally punched full of closely spaced wells, which were

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[1] For theoretical analysis of the various classes of decline curves, see Arps (1945) and Pirson (1946).

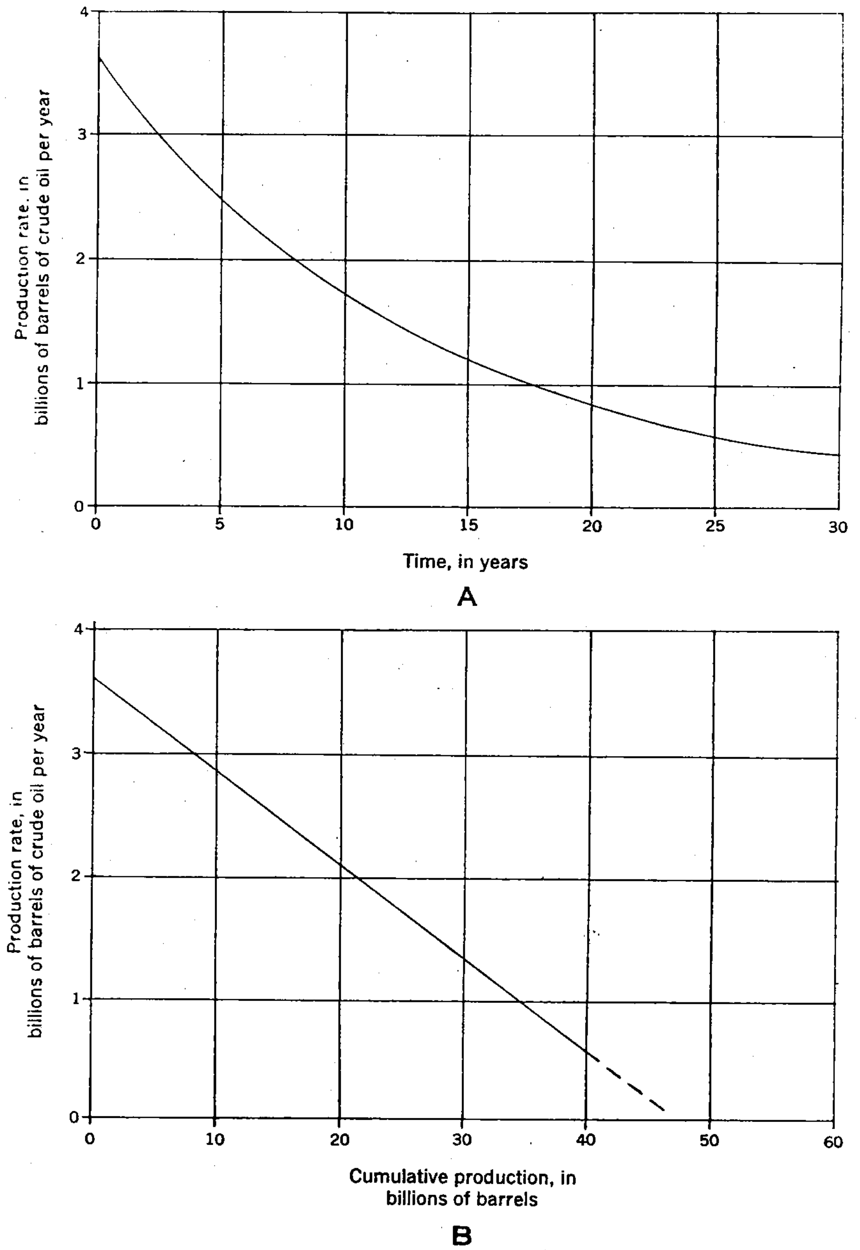

FIGURE 1.—Constant percentage decline curves.

pumped or allowed to flow without restriction. When natural gas was found ahead of, or with, the oil, it was generally withdrawn as quickly as possible to minimize delay in the production of oil. An ever-increasing mass of evidence before 1930 from field, laboratory, and theoretical research in reservoir engineering had shown, however, that such production practices were extremely wasteful. Investigation had proved that a much higher proportion of the total oil in the reservoir could be removed by restricting the rate of production from the outset in order to utilize more fully the natural energy in the reservoir. A massive conservation movement,[2] which got underway in earnest about 1930, has gradually changed general production practice from rapid early withdrawal, closely spaced wells, and reduced ultimate recovery, to restricted early production rates, wider spacing of wells, and increased ultimate recovery. Many major oil-producing States now have laws that prohibit wasteful production practices, and some States further restrict production to predicted market demand. Growing realization of the ultimate benefits of controlled production has led to ever-widening application of conservation measures on a voluntary basis.

With the advent of conservation, the meaning of the phrase "producing capacity" changed. Instead of being the maximum rate at which a well could produce, it became, for many wells, the highest producing rate commensurate with maximum economic ultimate recovery. This is generally called the "maximum efficient rate," usually abbreviated "M.E.R.". The M.E.R. is not an absolute value; it differs for different types of reservoirs and is subject to change as the reservoir is produced. Engineers do not always agree on the precise M.E.R. for a given reservoir. Moreover, the M.E.R. is determined by economic as well as physical factors—production rates lower than the M.E.R. would in most cases result in still greater ultimate recovery, "but once the rate is sufficiently low to permit the basic requirements [avoidance of waste] to be met, the incremental ultimate recovery obtainable through further reduction of the rate of production may be insufficient to warrant the additional deferment of a return and the additional operating expenses that would result from a prolongation of the operation" (Buckley, 1951, p. 151–152). However, the value of the M.E.R. concept in increasing ultimate recovery has been enormous, and a steadily increasing proportion of the oil wells in the United States is being produced under this philosophy.

When there is sufficient demand for domestically produced crude oil, the wells are produced at the M.E.R. producing capacity, or at total physical producing capacity for those wells (1) which need no restriction to avoid waste, or (2) which are operated without regard to good engineering practice. When there is oversupply of crude oil, the wells in most States are produced at average rates well below the M.E.R., in accordance with the allocations of the State regulatory bodies. The amount by which producing capacity exceeds the average producing rate is termed the "reserve producing capacity."

In summary, producing capacity of the United States is the sum of (1) the M.E.R.'s of those wells operated under the M.E.R. concept, and (2) the maximum producing rates of wells that need no restriction and of those not operated under good engineering practice. It is considerably less than the rate of production would be if all wells were "opened wide." The effect of restricted early production under the M.E.R. concept is to increase greatly the ratio of recoverable reserves to current producing capacity; any further restriction of the average rate of production to levels below M.E.R., to avoid overproduction, tends to increase this ratio still more for it tends to increase ultimate recovery still more.

During the era of unrestricted production, typical decline curves showed a steep decline in rate of production during the early life of the well, then a protracted period of slow decline. The effect of conservation practice—restricting early rates of production in the interest of greater total recovery—has been to flatten the steep decline and extend the average decline curve. The initial M.E.R. producing capacity can be maintained at the same level for a considerable length of time for many new wells operated under the M.E.R. concept, but eventually decline will set in (Ball, 1940, p. 143).

The spacing of wells has a decided effect on producing capacity. The sum of the producing capacities of two wells drilled close together is greater than the capacity of a single well, but is considerably less than twice the capacity of the single well because of mutual interference (Muskat, 1949, p. 899). Therefore, the general effect of wider spacing of wells (and, consequently, fewer wells) is to increase capacity-per-well, to decrease the producing capacity for the pool as a whole and to increase the time required to achieve ultimate recovery. Theoretically, the M.E.R. should be determined for the pool as a whole, and divided among the wells in the pool regardless of number, but in practice the more densely drilled pools are allowed to produce at a relatively higher rate for economic reasons. Majority opinion is that the ultimate recovery is virtually the same whether the spacing is the widest that will permit drainage from all parts of the reservoir, or whether the spacing is very close (Zimmermann, 1957, p. 337). Therefore, the trend toward wider average well spacing is another factor that tends to increase the ratio of producible reserves to current producing capacity.

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[2] For a recent full discussion of the history and effects of the conservation movement in the petroleum industry, see Zimmermann (1957).

Thus far, the discussion of producing capacity has dealt principally with crude oil. Where natural gas occurs with crude oil in the reservoir, good engineering practice requires that as much of the gas as feasible be retained in the reservoir to conserve reservoir energy. For such wells, the producing capacity for gas is limited by the M.E.R. for the oil. Where natural gas occurs in separate reservoirs, the gas can be produced at a much higher relative rate than crude oil, and without deleterious effects on ultimate recovery. The same is true for most deposits of "wet" gas from which natural gas liquids are recovered, although in some deposits careful pressure control, and therefore controlled production, is necessary to prevent condensation in the reservoir and loss in ultimate recovery.

ESTIMATES OF PRODUCING CAPACITY

A series of estimates (table 1) prepared through field-by-field inventories under the auspices of the National Petroleum Council and the Petroleum Administration for Defense indicate the growth of the Nation's present crude-oil producing capacity since World War II.[3] These quantities, although estimates rather than actual measurements, on the date of the survey, must by their nature have a high degree of accuracy. Virtually all pools are produced at their M.E.R. capacity rate at least occasionally and at least for short periods of time. These occasional actual measurements of capacity enable field engineers to estimate rather precisely the capacity at any given date. All the estimates in table 1 are based on maximum efficient rates.

No comparable estimates based on field-by-field inventory of the Nation's producing capacity for natural gas have been made.

Estimates of producing capacity for natural gas liquids (petroleum liquids recovered from natural gas) have been prepared and are also listed in table 1. These estimates, however, are based in part on the capacity and technology of existing processing plants rather than on the total quantity of such liquids available from existing wells. The proportion of natural gas that is treated could be increased, and the rate of recovery of liquids from natural gas could also be increased (Carney, 1951, p. 259) if warranted by economic conditions. The estimates for natural gas liquids, therefore, differ somewhat from those for crude oil.

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[3] A committee of the Independent Petroleum Association of America has also made yearly estimates of the Nation's crude-oil producing capacity since 1954, but those estimates are defined as "the average rate of production from existing wells that could be maintained for a period of from 6 to 12 months without further development and with no significant loss in ultimate recovery" (I.P.A.A. "Monthly," June 1958, p. 41). The I.P.A.A. estimates thus relate to a period of time, with some allowance for decline, and are therefore slightly less than the N.P.C. and P.A.D. estimates, which relate to a specific date.

TABLE 1.—*Estimates of producing capacity of the United States*

Date	Source[1] of estimate	Thousands of barrels daily	
		Crude oil	Natural gas liquids
1-1-46	--------	[2] 4,700	--------
1-1-51	NPC	6,727	573
1-1-52	PAD	7,200	--------
1-1-53	NPC	7,465	694
7-1-54	NPC	8,331	765
1-1-57	NPC	9,867	845

[1] NPC—National Petroleum Council: "Report of the National Petroleum Council Committee on Petroleum Productive Capacity," Oct. 3, 1957, table 2. PAD—Petroleum Administration for Defense: "Report on Crude Oil Productive Capacity," November 1952.

[2] Average production rate. It is generally agreed that U.S. oil wells were producing approximately at capacity near the end of World War II.

The growth in total producing capacity and in reserve producing capacity for crude oil in the United States since World War II is shown graphically in figure 5.

PROVED PETROLEUM RESERVES

Proved petroleum reserves refer to the quantity of petroleum yet to be produced from the underground pools as known from drilling so far. The proved reserves are still in the reservoirs; consequently, they cannot be acutally measured—they can only be estimated. The accuracy of an estimate of proved reserves of a pool cannot be fully determined until the pool has been produced to the abandonment stage—many years or many decades later.

METHODS OF ESTIMATING

Estimates of proved reserves are generally made either by use of decline curves, volumetric computations, or material balance calculations. In preconservation days, when production from most wells was unrestricted and continuous, decline curves were generally used to estimate reserves yet to be produced. As soon as there was sufficient production history to indicate the general shape of the decline curve, the curve was extrapolated to the assumed rate of production at which the well or pool would be abandoned, and the reserves were estimated from this extrapolated curve. The extrapolation of decline curves and the computation of estimated reserves therefrom may be accomplished either by graphical methods (Cutler, 1924) or by mathematical methods (Arps, 1945; Pirson, 1946). In figure 1*A*, for example, if the first 10 years represented recorded production and the rest of the curve were extrapolated, the estimated reserves producible in the 20 years subsequent to the date of the estimate would be the area under the extrapolated part of the curve, with each square representing 5 billion barrels; that is about 18 billion barrels. By extending the graph and extrapolation to the estimated production rate at time of abandonment, the total proved reserves could be similarly estimated. In figure 1*B*, if the estimate is made at the time the production rate had fallen to 2 billion barrels per year and the cumulative production had reached about 21 billion barrels, the extrapolated curve would indicate an ultimate production of about 45 billion barrels, the exact amount depending on the assumption as to how much production would never be realized because of abandonment of wells before complete exhaustion. The proved reserves would then be the estimated ultimate production minus the cumulative production at the time of the estimate.

With the advent of widespread restriction of production as a conservation measure, decline-curve methods of reserve estimation were largely replaced by volumetric methods and material balance calculations. Under conditions of curtailed production, the decline-curve methods were inapplicable until after production decline had set in—in many cases long after production had begun. The validity of decline-curve methods remains unquestioned, however, and they are still frequently used where applicable.

Volumetric methods of reserve estimation are based on estimates of total quantity of petroleum originally in the reservoir, the percentage that can be produced (recovery factor), and the expansion (for natural gas) or the shrinkage (for crude oil) that occurs in moving from the reservoir to the earth's surface. Estimates of the total petroleum originally in the reservoir, in turn, are based on (a) estimates of the total volume of the reservoir, (b) the effective porosity of the reservoir, (c) the proportion of that porosity that is occupied by petroleum, and (d) the compressibility of the reservoir. Available pertinent field and laboratory measurements—well logs, core analyses, and fluid analyses—are used to estimate the various factors, but all factors are subject to a greater or lesser error. Cores and fluid samples are but very small samples of large and, in many cases, highly variable systems; the exact volume of the reservoir is difficult to determine from scattered well logs, and this difficulty naturally becomes greater with increased well spacing; the estimated recovery factor is in many cases highly uncertain. Nevertheless, the volumetric estimates are useful and necessary. They may be made early in the life of the pool, and revised as better information becomes available. The proved reserves are derived by subtracting the cumulative production from the total ultimate recovery as estimated by the volumetric computations.

The material balance calculation is used to estimate reserves in certain types of reservoirs and to verify reserve estimates indicated by the volumetric method. The basis of the material balance calculation is the balance between the fluids in the reservoir and the fluids produced. At any particular time the withdrawals from the reservoir must equal the expansion of the fluids originally contained in the reservoir plus any influx of other fluids into the reservoir. Cumulative production, reservoir pressure, and reservoir fluid analysis data are required for this analysis. The accuracy of these data, which are normally available, obviously determine the accuracy of the reserve estimates. Material balance calculations are often considered unacceptable in the early development period of a field because of the difficulty in determining average reservoir pressure during this period. The proved reserves are determined by applying the estimated recovery factor to the calculated reserves and subtracting the cumulative production.

NATURE OF ESTIMATES

Estimates of proved reserves are expressed in precise units such as barrels or cubic feet, but it should be kept in mind that they are estimates and not actual measurements, and are subject to major revision as more information becomes available and new production techniques are developed. By whatever method the reserves are estimated, the longer the well or pool has been producing the more accurate is the estimate of the diminishing reserves, for there is more and better information on which to base the estimate. Immediately after a new oil pool is discovered, the assumptions as to its volume—and therefore the estimate of reserves—tend to be very conservative. As the pool is "drilled out" with development wells, and more is learned about the reservoir and its contained oil, the estimated ultimate recovery from the pool is generally revised upward. The table below illustrates this "lag element."

Period during which the fields were originally discovered [1]	Number of "giant" fields (capable of ultimate production exceeding 100 million bbl.) in the United States	
	As recognized at the end of 1948 [2]	As recognized at the end of 1958 [3]
Before 1899	4	4
1899–1908	17	19
1909–18	17	26
1919–28	41	52
1929–38	39	60
1939–48	12	32
1949–58	----	18
Total	130	211

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[1] Date of original field discovery from Oil and Gas Journal, v. 47, no. 39 (Jan. 27, 1949), p. 181–183, for the fields therein listed. Discovery dates of fields subsequently recognized as "giants" from "Oil and Gas Field Development in the United States and Canada, Yearbook, 1958 (Review of 1957)" (National Oil Scouts and Landmen's Assoc., v. 28, Austin, Tex.).

[2] Oil and Gas Journal, v. 47, no. 39 (Jan. 27, 1949), p. 181–183. Fields consolidated during the 1949–58 period (Sho-veltum, Okla., and Eunice-Monument, N. Mex.) were considered as single fields. Seeligson, Aqua Dulce, and La Gloria, Tex., were considered as separate fields.

[3] Oil and Gas Journal, v. 57, no. 4 (Jan. 26, 1959), p. 141–147. Mexia field, Texas, added to list.

If one considers only the right-hand column of the foregoing tabulation, it appears that there has been an alarming decrease in the number of large fields discovered per decade in the last 20 years. Some authors (Ayres and Scarlott, 1952, p. 39; Pogue and Hill, 1956, fig. *7D*, p. 20) have drawn such a conclusion from similar statistics. But because of the lag element in reserve estimation, recent trends based on proved reserve statistics are deceptive. Thus, the above table shows that at the end of 1948, only 12 of the fields discovered during the preceding 10 years were recognized as "giants"—10 years later, the count had grown to 32. The table also shows that many fields are more than 20 years old—some are more than 40 years old—before their giant proportions are recognized! The fact that 18 "giant" fields less than 10 years old were recognized at the end of 1958 as compared with 12 at the end of 1948 suggests that the number of "giant" fields discovered per decade may still be rising. But because of the lag element, probably 20 years, and possibly a much longer time, must elapse before the answer to that question will be known with reasonable certainty. It is most unlikely, however, that new "giant"-field discoveries are increasing proportionately to the increase in exploratory effort.

It should be emphasized that upward revision of reserve estimates results not only from additional drilling (development drilling) that increases the known extent of a pool, but frequently results from upward revision of estimates for previously drilled parts of pools. The giant East Texas field was dicovered in 1930. By the end of 1935 the field had largely been "drilled out" with 19,519 producing wells (Ralston, 1936, p. 364). At that time the ultimate recovery (cumulative production plus proved reserves) was estimated to be about 2⅛ billion barrels of crude oil (Garfias and Whetsel, 1936, p. 214). By the end of 1957, however, more than 3 billion barrels had been produced, and the ultimate recovery was estimated to exceed 5 billion barrels (Oil and Gas Journal, v. 56, no. 4 (Jan. 27, 1958), p. 168).

The history of national estimates of proved petroleum reserves has been summarized in another publication (U.S. Geol. Survey, 1951, p. 16–30). The most widely known and frequently quoted estimates of proved petroleum reserves on a national scale are those prepared yearly by the Committee on Petroleum Reserves of the American Petroleum Institute (crude oil) and the Committee on Natural Gas Reserves of the American Gas Association (natural gas and natural gas liquids). A summary of the A.P.I. and A.G.A. estimates for the United States since World War II is reproduced in table 2, and full statements of the nature of the A.P.I. and A.G.A. estimates are quoted on page H-33 of this report.

TABLE 2.—*Summary of proved reserves in the United States as reported for 1946 and thereafter*

[Source of data: Reports on proved reserves of crude oil, natural gas liquids, and natural gas in the United States and Canada, v. 13, Dec. 31, 1958, published jointly by American Gas Association and American Petroleum Institute, New York, and Canadian Petroleum Association, Calgary, Alberta]

Year	Added during the year			Increase in underground storage (4)	Production during year[1] (5)	Estimated proved reserves as of end of year (6)	Increase over previous year (7)
	Revisions of previous estimates and extensions to known fields (1)	Discoveries of new fields and new pools in old fields (2)	Total (3)				
Crude oil (thousands of barrels of 42 U.S. gal.)							
1946	2,413,628	244,434	2,658,062	----------	1,726,348	20,873,560	931,714
1947	2,019,140	445,430	2,464,570	----------	1,850,445	21,487,685	614,125
1948	3,398,726	396,481	3,795,207	----------	2,002,448	23,280,444	1,792,759
1949	2,297,428	890,417	3,187,845	----------	1.818,800	24,649,489	1,369,045
1950	1,997,769	564,916	2,562,685	----------	1,943,776	25,268,398	618,909
1951	4,024,698	389,256	4,413,954	----------	2,214,321	27,468,031	2,199,633
1952	2,252,860	496,428	2,749,288	----------	2,256,765	27,960,554	492,523
1953	2,704,450	591,680	3,296,130	----------	2,311,856	28,944,828	984,274
1954	2,287,231	585,806	2,873,037	----------	2,257,119	29,560,746	615,918
1955	2,393,767	476,957	2,870,724	----------	2,419,300	30,012,170	451,424
1956	2,507,114	467,222	2,974,336	----------	2,551,857	30,434,649	422,479
1957	2,008,603	416,197	2,424,800	----------	2,559,044	30,300,405	−134,244
1958	2,293,513	314,729	2,608,242	----------	2,372,730	30,535,917	235,512
Natural gas liquids (thousands of barrels of 42 U.S. gal.)							
1946	(2)	(2)	(2)	----------	(2)	3,163,219	----------
1947	192,237	59,301	251,538	----------	160,782	3,253,975	90,756
1948	405,874	64,683	470,557	----------	183,749	3,540,783	286,808
1949	294,211	92,565	386,776	----------	198,547	3,729,012	188,229
1950	707,879	58,183	766,062	----------	227,411	4,267,663	538,651
1951	648,497	75,494	723,991	----------	267,052	4,724,602	456,939
1952	475,170	81,668	556,838	----------	284,789	4,996,651	272,049
1953	648,047	95,922	743,969	----------	302,698	5,437,922	441,271
1954	20,830	86,520	107,350	----------	300,815	5,244,457	−193,465
1955	447,160	67,348	514,508	----------	320,400	5,438,565	194,108
1956	715,764	94,056	809,820	----------	346,053	5,902,332	463,767
1957	8,884	128,508	137,392	----------	352,364	5,687,360	−214,972
1958	749,956	108,250	858,206	----------	341,548	6,204,018	516,658
Natural gas (millions of cubic feet—14.65 psia at 60°F)							
1946	(3)	(3)	17,729,152	(3)	4,942,617	160,575,901	12,786,534
1947	7,570,654	3,410,170	10,980,824	(3)	5,629,811	165,926,914	5,351,013
1948	9,769,483	4,129,089	13,898,572	51,482	6,007,628	173,869,340	7,942,426
1949	8,061,429	4,612,870	12,674,299	82,746	6,245,041	180,381,344	6,512,004
1950	9,172,381	2,877,351	12,049,732	54,301	6,892,678	185,592,699	5,211,355
1951	13,013,606	3,039,385	16,052,991	132,751	7,966,941	193,811,500	8,218,801
1952	8,934,470	5,411,043	14,345,513	198,850	8,639,638	199,716,225	5,904,725
1953	13,371,355	7,081,661	20,453,016	[4] 516,431	9,238,540	211,447,132	11,730,907
1954	4,632,309	4,966,894	9,599,203	90,906	9,426,509	211,710,732	263,600
1955	16,298,125	5,719,069	22,017,194	87,637	10,118,118	223,697,445	11,986,713
1956	19,214,604	5,636,476	24,851,080	133,970	10,907,926	237,774,569	14,077,124
1957	11,118,319	8,998,993	20,117,312	179,733	11,502,359	246,569,255	8,794,686
1958	13,388,808	5,611,098	18,999,906	57,902	11,485,026	254,142,037	7,572,782

[1] Estimated in part. Production figures for natural gas refer to net production.
[2] Data not available.
[3] Not estimated.
[4] All native gas in storage reservoirs formerly classified as a natural gas reserve is included in this figure.

The statistics in table 2 do not include the new State of Alaska, inasmuch as there has been very little drilling in Alaska and the proved reserves are consequently relatively small. Estimates of proved reserves of Alaska at the end of 1957 range from about 62 million to about 112 million barrels of crude oil, and from about 232 billion to about 307 billion cubic feet of natural gas. These estimates were made by members of a committee of Geological Survey geologists familiar with the area.

It is to be noted in table 2 that of the oil "added during the year," by far the largest proportion is through revision of previous estimates and extensions of known fields—another indication of the "lag element." During World War II, the Petroleum Administration for Defense made a statistical study in which extensions and revisions were credited back to the year of discovery (Buckley, 1951, p. 18–22). Some of the results of this study are summarized in figure 2. Statistics so prepared in 1945 showed, for example, "reserves" of about 22¾ billion barrels at the end of 1936, compared to the approximately 13-billion-barrel estimate made at the end of 1936 by the American Petroleum Institute. The two "reserve" figures are not actually comparable, for many development wells necessary to produce the larger quantity were not drilled until after 1936, and the decision as to whether a new well represents an extension or a new discovery is in some cases arbitrary. The statistical technique does, however, provide a good illustration of the magnitude of the "lag element" (fig. 2).

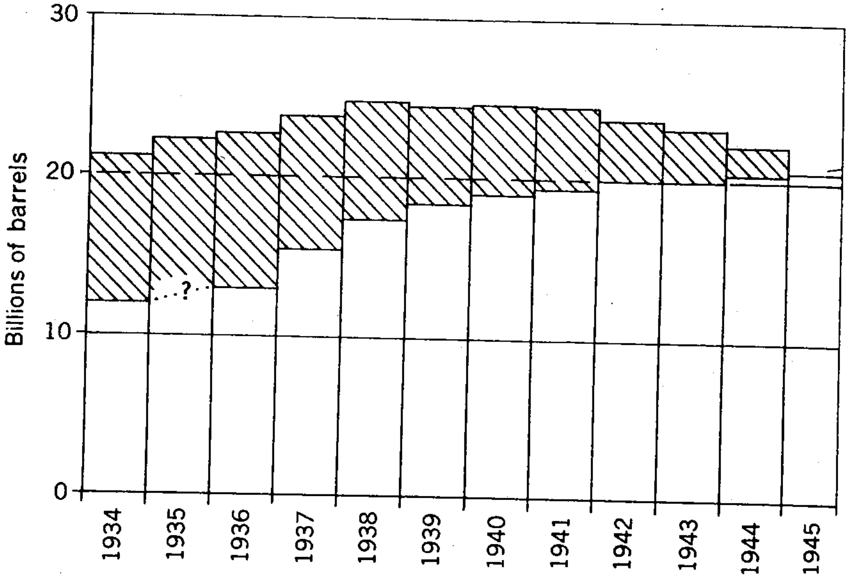

FIGURE 2.—Effect of crediting extensions and revisions back to year of discovery. Lower, unshaded bars are the American Petroleum Institute's yearly estimates of proved reserves of crude oil in the United States at the end of each year (not estimated in 1935). Shaded bars are the quantities added by crediting extensions and revisions, as known in 1945 back to years of discovery. (Adapted from Buckley, 1951, chart 1, p. 21.)

It is tempting to interpret the quantitative expressions of total "new oil" added during the year (table 2, col. 3) as a measure of the rate of development of new supply, and to draw conclusions as to future supply by projecting trends based on these statistics. Thus, Pogue and Hill (1956, fig. 8*D*, p. 21) have plotted and projected the statistics directly, and have called them "annual discovery rate." Similarly, Davis (1958, p. 106, and fig. 1, p. 109) has divided the yearly totals (table 2, col. 3) by the total footage drilled yearly to derive a statistical element termed "drilling return" expressed in barrels per foot drilled, and has based conclusions on projected trends in the "drilling return." But because of the "lag element" in reserve estimates, the more recent the estimate, the more conservative it is likely to be. Consequently, any trends based on recent estimates give a more pessimistic picture than knowledge of past performance warrants.

The yearly estimates of proved reserves do not purport to be a measure of the discovery rate, and should not be interpreted as such. The proved-reserve estimates have also been commonly misinterpreted as reflecting the true rate of increase in the quantity of petroleum producible from existing wells without change in production practice, or as reflecting the full quantity that is economically producible from existing wells. The degree of unreliability of such interpretations of proved-reserve statistics is best examined in the light of the data on producing capacity.

RELATION TO PRODUCING CAPACITY

The decline-curve principle makes possible a comparison of recent National estimates of proved reserves with the estimates of producing capacity. Producing capacity is more accurately determinable (p. H–8) and estimates of producing capacity are current; that is, they are not subject to the "lag element."

From our knowledge of the behavior of individual wells, it is certain that if there were no further drilling in the United States and if all the oil wells began to be produced at their producing capacity, the total rate of production would, after the initial sharp increase to the capacity rate, begin to decline. If the wells were continuously produced at capacity year after year without change from current production practice, the rate of production would decline continuously until the last well had reached the economic limit. At that time the cumulative production since the beginning of this hypothetical period would, of course, equal the true quantity of reserves that existed at the beginning of the period. The rate-cumulative curve would have the general form of that shown in figure 1*B*, though it might have a different slope and it might be slightly curved. In this analogy, the value along the ordinate (vertical) is the producing capacity, because the production rate is at capacity, and the value along the abscissa (horizontal) is reserves (minus, of course, a relatively small quantity that would never be produced because of the abandonment of wells, for economic reasons, before they had been produced to exhaustion). It is readily apparent in figure 1*B* that the value along the abscissa is proportional to the value along the ordinate; therefore, reserves are approximately proportional to producing capacity. In other words, with the same production practice and in similar reservoirs, twice the producing capacity means approximately twice the recoverable reserves.

Let us now apply this relation to recent statistics. The National Petroleum Council's estimates of the Nation's crude-oil producing capacity on January 1, 1951, and on January 1, 1957, were, respectively, about 6.7 million barrels and 9.9 million barrels daily (table 1). Assuming that there was no significant change in general production practice that would result in a change in slope of the rate-cumulative curve,[4] the reserves at the end of 1956 were about 9.9 million/6.7 million, or about 1.47, times the reserves at the end of 1950—that is, an increase of about 47 percent. The American Petroleum Institute proved-reserve estimates (table 2), however, showed an increase of only about 20 percent over the same period.

In view of this marked difference, careful consideration should be given as to whether there has been any significant change in production practice during the period that would change the slope of the hypothetical rate-cumulative curve. If the slope has remained unchanged, as assumed above, the ratio of producible reserves to producing capacity has remained constant. Changes in production practice that increase the ratio of reserves to producing capacity have the effect of decreasing the slope of the rate-cumulative curve; in other words, if this slope is becoming more gentle, reserves are increasing at a faster rate than producing capacity. Changes in production practice that decrease the ratio of reserves to producing capacity have the opposite effect. As discussed in a preceding section

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[4] Change in the average physical characteristics of producing reservoirs could also result in a change in slope of the hypothetical rate-cumulative curve, but it seems very unlikely that there has been any significant change in this respect during the period discussed. There has been a notable increase in the number of low-permeability and stratigraphic-trap reservoirs discovered and developed since World War II. However, these constitute but a small fraction of the total, probably insufficient to significantly change the National average.

(p. H-4), the long-term trends in production technology since the beginning of the conservation movement have been toward increasing the ratio of reserves to producing capacity. With the continuing trend toward wider spacing of wells, and with an increasingly larger proportion of wells operated under the M.E.R. concept as new fields are developed, it is likely that any changes in the hypothetical rate-cumulative curve are probably toward a more gentle slope, and that the quantity of unproduced reserves is increasing at a more rapid rate than producing capacity.

The National Petroleum Council (1957, p. 8) has listed several recent technological trends—multiple completion of wells, hydraulic fracturing of producing formations, waterflooding—as tending to decrease the ratio of reserves to producing capacity. But these technological trends, it should be noted, affect a relatively small percentage of wells thus far; and each of the practices adds to producible reserves as well as to producing capacity; consequently their effect on that ratio is likely to be small. By contrast, increased well spacing and production control affect a much larger number of wells, and both tend to decrease total producing capacity with no decrease in producible reserves—indeed, production control serves to increase the producible reserves.

In summary, the recent rate of increase in producible reserves of crude oil under present production practice as suggested by recent estimates of proved reserves seems to be far too low when examined in the light of the rate of increase in producing capacity, the decline-curve principle, and known technological trends that affect the ratio of reserves to producing capacity.

If the recent proved-reserve estimates do not reflect the rate of increase of new supply, the question arises as to what extent such estimates reflect the full quantity economically producible from existing wells. The decline-curve method could be used to estimate this quantity, as of the date of the most recent estimate of producing capacity, if we knew the nature of the decline curve that would obtain if the wells had thenceforth been produced at capacity. The National Petroleum Council (1957, p. 2) estimated U.S. crude-oil producing capacity on January 1, 1957, at about 9.9 million barrels daily, and made a qualified estimate that the decline in productive capacity in the first year might be about 7.5 percent if there were no further drilling, and if production were at full capacity (National Petroleum Council, 1957, p. 4). The curves on figure 1 were plotted with a beginning producing capacity of approximately 9.9 million barrels daily (about 3.6 billion bbl annually), and an assumed constant-percentage decline of 7.5 percent yearly. As readily seen in figure 1*B*, these assumptions would indicate that reserves producible from existing wells (Jan. 1, 1957) exceeded 45 billion barrels. This compares with the January 1, 1957, estimate of 30.4 billion barrels of proved reserves prepared by the American Petroleum Institute (table 2).

Of course, the exact shape of the decline curve that would obtain if all wells were produced at capacity is not known, but the assumption that it would follow the constant-decline pattern results in a more conservative estimate of producible reserves than would be obtained by use of other common types of curves (Cutler, 1924, p. 11). The National Petroleum Council's figure of 7.5 percent for the first year's decline is only an estimate, admittedly based on insufficient data. It is clear, however, that the American Petroleum Institute reserve estimates reflect only part of the total quantity economically producible from existing wells.

RELATION TO TECHNOLOGY

Proved-reserve statistics, by definition, make no allowance for future application of improvements in technology (p. H–33). But technological advances frequently increase the amount of oil recoverable from existing wells. For example, only part of the oil in place is producible by primary production methods, but large additional amounts have been successfully recovered from many wells by injection of water, natural gas or other light hydrocarbons, air, or chemicals into the reservoir. Certain experimental techniques of inducing heat in the reservoir show promise of converting to producible reserves some petroleum accumulations too viscous to be produced by conventional methods. The quantity of oil recoverable by these secondary methods, relative to the amount recoverable by primary methods, is especially large in most so-called volumetric reservoirs, and the proportion of such reservoirs among recent discoveries has been increasing. Some pools whose production had declined to low levels have been rejuvenated by secondary-recovery methods, and a new decline cycle inaugurated. In making its reserve estimates the American Petroleum Institute committee generally does not consider secondary-recovery oil until the projects are actually in operation. This accounts in part for the difference between American Petroleum Institute estimates and the amount of producible oil indicated by producing capacity and estimated potential rate of decline in producing capacity, as discussed above. The National Petroleum Council's estimate of potential 7.5 percent decline makes allowance for increased application of secondary-recovery techniques and other technologic advancements in the future.

RESERVES OF NATURAL GAS AND NATURAL GAS LIQUIDS

Estimates of proved reserves of natural gas and contained natural gas liquids are generally made by volumetric methods and are subject to the same sources of error as those for crude oil. A much larger proportion of the original reservoir content is producible than for crude oil. The gas can be produced until the pressure differential between the reservoir and the gathering pipeline decreases to a point at which the rate of production is too low for profitable operation. The quantity considered as proved reserves depends to some extent on the assumption as to what the "abandonment pressure" will be. The market for natural gas is expanding markedly, and abandonment pressures will no doubt decrease, with consequent increase in the gas considered as "reserves." It is technologically feasible—and locally economically feasible—to create artificially a near-vacuum at the wellhead and to pump the gas into high-pressure pipelines. Thus, in addition to the difficulties of determining underground volumes, estimates of proved reserves of natural gas are subject to considerable change due to economic changes. Moreover, newly discovered natural gas fields are, on the average, developed more slowly than newly discovered crude-oil fields because of greater oversupply of natural gas, the necessity for pipeline outlets, and the reluctance of some companies to produce gas for interstate sale under present Federal regulations. Hence, the "lag element" is likely to be even greater for natural gas.

Proved-reserve estimates of natural gas liquids are based in part on the number, distribution, and technology of "separators or extraction plants, now in operation, under construction, or planned in the immediate future"; consequently, they do not profess to be a measure of the quantity of such liquids producible from all existing wells.

ULTIMATE "RESERVES"

The quantity of petroleum in the earth's crust is finite; continued extraction and consumption must eventually exhaust the supply. New petroleum is doubtless forming constantly, but probably at such an exceedingly slow rate as to be negligible as a source of supply. Naturally, it would be of great interest to know what the eventual total supply will be, because then we could determine how near we are to exhausting it.

From time to time, individuals or groups have attempted to guess the total quantity of petroleum that has been and can be profitably found and produced in the United States or in the world, and such conjectures have commonly been called "estimates of ultimate reserves." The estimates include (a) the economically producible petroleum already found, including past production, and (b) the predicted amount that will be found and produced in the future.[5]

These estimates have been made with several assumptions. Some refer only to petroleum producible by primary methods; others consider only petroleum above a certain depth. Most estimates assume static economics and technology, although Netschert (1958) has recently attempted to show the effect of technological development. For many published estimates, the assumptions are not stated, and the various estimates are consequently difficult to compare.

No attempt is made here to list the various estimates that have been published. Early estimates have been conspicuously inadequate; time after time the quantity estimated as "ultimate" has been closely approached or exceeded within a decade by the quantity "petroleum already found," and estimates consequently were revised sharply upward. Netschert (1958, p. 11–19) has summarized and compared recent estimates of ultimate crude-oil "reserves" of the United States. Since Netschert's study, Weeks (1958, p. 434) has revised his 1948 estimate sharply upward, partly because of a different basis, to 240 billion barrels of crude oil producible by primary methods, with possibly an equally large amount eventually recoverable by secondary methods. A recent survey by the Oil and Gas Journal (v. 56, no. 20, May 19, 1958, p. 114) showed that several major petroleum companies estimated the Nation's ultimate "reserves" of crude oil to be about 300 billion barrels or more. None of these estimates have included the new State of Alaska. The ultimately recoverable crude oil in Alaska and adjacent continental shelves has been roughly estimated by a committee of Geological Survey geologists as approximately 30 billion barrels.

It has been shown (Hubbert, 1957, p. 11–13) that for an exhaustible resource such as petroleum, rate of production (assuming infinite demand) must inevitably rise to a peak and then decline to zero. For petroleum, the period of decline must be an extended one, because of physical limitations on the rate at which it can be withdrawn from natural reservoirs. Several investigators have used this principle, together with production history and estimates of ultimate "reserves," to project the production curve into the future and thereby predict when production must begin to decline because of the physical limitations imposed by the total quantity producible. In other words, such projections attempt to forecast the date when maximum produc-

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[5] Use of the term "reserves" for this concept is rather unfortunate—past production is not reserves, and there is considerable question whether undiscovered supply should be termed reserves. The concept could be accurately termed "ultimate production, assuming infinite demand at present general price levels." But such terminology is awkward, and the use of the shorter, now well-entrenched term "ultimate 'reserves'" will be continued in this report, with "reserves" enclosed by quotation marks.

ing capacity will be achieved. In 1956 Hubbert estimated the United States' ultimate "reserves" of crude oil to be 150 billion barrels (Hubbert, 1957, p. 15), and showed that on this basis the rate of production would necessarily begin to decline after reaching a peak of about 2¾ billion barrels in about 1965. But by the beginning of 1957, crude-oil producing capacity in the United States had already risen to about 3.6 billion barrels per year (approximately 9.9 million barrels daily) (table 1). Thus, the production rate already would have risen well above 3 billion barrels per year had a sufficient market existed for domestically produced crude oil.

Because the quantity of ultimate "reserves" has a direct bearing on future producing capacity, the possibilities of arriving at a truly dependable estimate of ultimate "reserves" should be carefully appraised. The discussion that follows will show why earlier estimates of ultimate "reserves" have proven so undependable, and why present estimates are likely to prove unreliable as a basis for conclusions as to future rate of availability.

As stated earlier, ultimate "reserves," consist of (a) economically producible petroleum already found, and (b) undiscovered economically producible petroleum. The first fraction is very important, for it constitutes not only a sizable fraction of the ultimate "reserves," but also the principal "yardstick" the estimator must use in considering the other fraction, the undiscovered quantity.

Petroleum already found includes cumulative production to date, and petroleum yet to be produced from known pools. Cumulative production, for crude oil, is essentially a measured quantity. For natural gas and its associated natural gas liquids, production statistics include only very rough estimates of the amounts wasted by venting or flaring in the preconservation period.

The quantity of petroleum yet to be produced from known pools, as pointed out in the discussion of proved reserves, is impossible to measure. It includes proved reserves, plus the amounts that doubtless will be added in subsequent years as a result of revisions of estimates for presently drilled areas, plus the amounts that similarly will be added as a result of development drilling of recent (and many not-so-recent[6]) discoveries. Most estimators of ultimate "reserves" seem to have considered the quantity of petroleum found so far to be the sum of cumulative production and American Petroleum Institute-American Gas Association proved "reserves," apparently neglecting the large quantities that history has taught us will be added to the proved-reserve estimates through "extensions and revisions" even if there were

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[6] A study by the Oil and Gas Journal (v. 55, no. 51, Dec. 23, 1957, p. 81–82) showed that approximately half the new development wells drilled in 1955 in the major producing States were in fields more than 16 years old.

no further discoveries. Inasmuch as there are no real measures of all the components of petroleum-already-found, the even more formidable problem of estimating undiscovered petroleum must be faced without a precise yardstick.

A crude yardstick can be fashioned from available data, however. The statistics are more complete for crude oil, and these will be used for an example. Cumulative production of crude oil in the United States at the end of 1958 was about 60 billion barrels; the American Petroleum Institute estimate of proved reserves at that time was about 30 billion barrels (table 2)—a total so far of 90 billion barrels. How much will eventually be added to proved-reserve estimates for pools discovered through 1958 cannot be determined, but it is certain that the amount will be large. The evidence from producing-capacity estimates (p. H-16—H-18) indicates that proved-reserve estimates represent only part of the amount economically producible from existing wells, and substantial upward revisions will doubtless be necessary. Moreover, the large amount of field drilling required to fully develop the already discovered fields will result in large increments ("extensions") to the proved-reserve estimates. The total of revisions and extensions applicable to pools discovered through 1958 will probably not be known for decades, but the statistical technique of crediting extensions and revisions back to the year of discovery gives some indication of the magnitude expectable. The 1945 study (fig. 2) showed that extensions and revisions applicable to pools discovered through 1934 and 1936, respectively, had, within the first decade, reached a total almost as great as the original proved-reserve estimate.[7] Thus it is not unlikely that future extensions and revisions for pools discovered through 1958 similarly may be of general magnitude about equal to the original 1958 proved-reserve estimate of 30 billion barrels. If so, the total quantity of crude oil produced and yet to be produced from pools discovered through 1958 is probably on the order of 120 billion barrels. In any case, it may be conservatively assumed that 100 billion barrels had been found by the end of 1958.

In tackling the problem of the probable magnitude of undiscovered petroleum, geology must be the principal guide. But about all that a geologist can do in advance of drilling is to classify, on the basis of existing knowledge, an area or specific location as favorable, unfavorable, or impossible for finding petroleum. Such technical guidance has resulted in a much better rate of success than random drilling, but the only way to determine the presence of oil underground is to drill holes and determine the fluid content of all potentially petroliferous strata.

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[7] The American Petroleum Institute does not publish the details of yearly extensions and revisions by pools; consequently a more up-to-date statistical study of this type is not feasible from published data.

Holes drilled to find new pools or "long extensions" to existing pools are called "exploratory" holes (Blanpied, 1958, p. 1127); the much more closely spaced holes drilled to develop known pools are called "development" holes. With these considerations in mind, and with the crude yardstick, a quantitative approach to the problem of ultimate "reserves" can be pursued a little further.

The National Petroleum Council (1952, p. 54), in a summary of a symposium conducted by the American Association of Petroleum Geologists, placed the area of the United States and adjacent continental shelves that has favorable prospects for the discovery of petroleum at 1,860,000 square miles. The thickness of sedimentary rocks in which petroleum may occur is nowhere less than 1,000 feet in this area, and in some of the area it exceeds 20,000 feet—the average doubtless exceeds 8,000 feet. Known commercial oil pools range in areal extent from a few acres to more than 200 square miles—many important pools are less than a square mile in extent, and such pools may underlie or overlie any part of other pools with greater areal extent.[8] To explore all the 1,860,000 square miles to a depth of 20,000 feet or to the base of the sedimentary rocks, whichever is reached first, would require exploration drilling to an average depth of at least 6,000 feet. An average density of 1 well for each 2 square miles—which would miss some important pools—would require more than 5 billion feet of exploratory drilling.

Statistics on exploratory footage drilled are available only as far back as 1938, and these show a total of about 770 million feet of such drilling in the 1938–58 period (Blanpied, 1959, p. 1130–1131). The National Petroleum Council (1952, p. 55) estimated that 140,000 exploratory wells had been drilled in the United States through 1950. Of this total, about half were drilled in the 1938–50 period (Blanpied, 1958, p. 1136), leaving about 70,000 exploratory wells for the pre-1938 period. Generously assuming an average depth of about 3,000 feet for these early wells, it is estimated that roughly 210 million feet of exploratory drilling was done before 1938. This gives an estimated total of about 980 million feet of exploratory drilling throughout 1958—less than one-fifth of the more than 5 billion feet that would be required for even near-exhaustive exploration of the potentially productive area.

The foregoing statistics refer only to the United States before the admission of Alaska to the Union. The new State contains an addi-

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[8] This vertical relation may not be generally understood by those not familiar with the petroleum industry. A petroleum "field" (the areal designation) may be underlain by several "pools" at various depths. The pools are discrete occurrences, and their outlines as projected to the surface rarely coincide. In 1957, for example, some 244 new pools were found by holes deliberately drilled to find new pools above (shallower pool tests) or below (deeper pool tests) known pools; in addition, at least 136 new pools were discovered accidentally in the drilling of field-development wells (Blanpied, 1958, p. 1134).

tional estimated 250,000 square miles underlain by potentially favorable rock in which there has been very little exploratory drilling.

Of course, geometrically spaced drilling to provide a density of 1 exploratory well for each 2 square miles will never occur—as in the past, exploratory wells in some areas will be drilled with a greater density and in other areas with a far less density, depending largely on relative favorability as indicated by previous drilling. That average density will never be reached if the density of commercial pools in a considerable part of the unexplored rock proves to be too sparse for economic exploration. But this much is certain: it cannot be safely assumed that even the 20-percent mark has been reached in exploration for petroleum in the United States, excluding Alaska and excluding rocks deeper than 20,000 feet. There is no imminent lack of potentially productive unexplored rock.

For those parts of the unexplored rocks in which the natural incidence of petroleum is approximately the same as in those already explored, relatively larger quantities of reserves will be developed than in the past because of technological development. As we have seen, constant improvement in production practice and wider and wider application of those improvements have meant greater and greater percentage recovery of the total petroleum in the reservoir. New techniques, especially formation-fracturing, have made production possible from reservoirs that were passed up in previous years because their natural permeability was too low for profitable exploitation. Improvements in techniques of detecting petroleum during exploratory drilling have made such drilling more conclusive—many pools have been penetrated in past years by exploratory holes but not detected. For example, in 1957, 20 entirely new fields were discovered by reentering and retesting old "dry holes" (Blanpied, 1958, p. 1134). Thus, because of technological progress, the natural incidence of oil need not be as great in the unexplored rocks as in those already explored to yield an equal amount of economically producible oil for the same amount of exploration.

With the crude yardstick of at least 100 billion barrels of oil found so far, and a rough appraisal of the extent of exploration so far, an objective estimate of the approximate minimum ultimate "reserves" appears to be in sight. The effect of technological development cannot be appraised quantitatively, but it is important in comparing unexplored areas with those already explored. One remaining factor is needed—is the average natural incidence of petroleum in the unexplored rocks the same as in those already explored, or if greater or less, how much greater or less? This is doubly important, for if there are areas in which the natural incidence is a great deal less, most deposits in those areas may never be found because excessive exploration costs will discourage drilling. It is in the evaluation of this factor—relative favorability of the unexplored rocks—that the quantitative approach breaks down, and estimation changes to conjecture. The explanation of why this is true requires a brief consideration of the history and nature of petroleum geology.

Knowledge of the geologic occurrence of petroleum is constantly evolving. Until about two decades ago petroleum geology was dominated by the anticlinal theory, which held that oil and gas, being less dense than water, migrate to the crests of upfolds of the containing strata. Application of that theory has been highly successful. Development drilling of the pools found, however, demonstrated that in many fields the entrapment of petroleum was due to structural relations other than anticlinal, and in a great many others, the entrapment was due principally to lateral changes in the character of the containing strata themselves—so-called stratigraphic traps. Similarly it was once thought that little petroleum would be found in rocks other than sandstone; we now know that other rock types can be prolific producers. As such knowledge has grown, our bases for evaluating unexplored areas as favorable or unfavorable have changed. At one time areas not known to contain anticlines were considered unfavorable or impossible. With the growing realization that enormous quantities of petroleum occur in stratigraphic traps, such areas must be considered favorable if known to have rock types and general stratigraphic conditions similar to those in productive areas.

The evolution of knowledge as to the geologic occurrence of petroleum is still going on. Every year discoveries are made in strata not previously known to be productive, and new variations in stratigraphic and structural conditions that caused entrapment are frequently found. Time after time in the past large areas of thick sedimentary rocks have been condemned on the basis of then-existing knowledge, only to have those areas turn out to be highly productive. Geologists have greatly improved their ability to classify areas as potentially productive, but any prediction as to the actual quantity of petroleum in unexplored ground is purely conjectural until, for one thing, the list of geologic settings in which petroleum occurs is more nearly complete.

Even if all the geologic settings favorable for petroleum were known, it would still be necessary to predict the incidence of those settings in the unexplored rocks. If petroleum occurred only on anticlines, this would be relatively simple, for many anticlines can be detected from surface study, and buried ones can generally be detected by geophysical surveys. But the search for stratigraphic traps requires very detailed information on the nature and distribution of rock types and the geologic history. Much of this information can be obtained from painstaking study of the rocks where they crop out, but relatively little of the prospective area has been so studied. Furthermore, much of the kind of information needed for realistic appraisal can be obtained only through actual drilling. Each new well adds information that permits a more intelligent appraisal of future prospects, and this process will continue indefinitely. Much exploratory drilling is done in relatively densely drilled areas, not because they are necessarily more favorable intrinsically, but because subsurface information useful in guiding exploration is more abundant. Hence any quantitative estimate of the favorability of an area in advance of a very substantial amount of drilling is a conjecture, at best.

The foregoing discussion explains why early estimates of ultimate "reserves" have proved to be so short of the mark, and why it is still impossible to predict accurately the quantity of oil yet to be discovered in the United States. A vast amount of unexplored rock appears to be geologically favorable—only extensive further drilling and geologic study will tell just how favorable. From present geologic evidence, there is little likelihood that the quantity of undiscovered oil will impose a limitation on the industry's ability to continue to increase crude-oil producing capacity at least through the next 10–20 years, and probably for a considerably longer time.

Thus far the discussion of ultimate "reserves" and discovery prospects has dealt mainly with crude oil. Much of the discussion applies equally well to natural gas and its contained liquids, for they are genetically associated with crude oil and are similar in geologic occurrence. Most natural gas discoveries have been a byproduct of the search for crude oil, and natural gas and natural gas liquids have traditionally been in considerable oversupply in regard to known quantities.

In regard to the quantities of natural gas and natural gas liquids yet to be discovered, the outlook is even more reassuring than for crude oil. The principal reason for this is that a unit volume of reservoir pore space can contain increasing quantities of natural gas with increasing depth, because of the higher natural pressures. The average depth of exploration has increased continuously in the past and will doubtless continue to increase. Accordingly, discovery of increasingly greater quantities, relative to crude oil, of natural gas and natural gas liquids may be expected.

The following statement, made in 1951 (U.S. Geol. Survey, 1951, p. 35), seems to be equally pertinent today:

> No precise statement as to the amount of potential reserves of oil and gas in the United States can yet be made. If the future can be judged by the past, oil and gas will be found in sufficient quantities for many years to come. In the United States adequate production has been a direct function of economic incentive. Until the unpredictable date at which that incentive fails to provide the needed supplies, there will be no convincing evidence that we have reached the limits of our ability to expand the potential ultimately recoverable reserves of petroleum.

EXPLORATORY SUCCESS

As discussed in the preceding section, an abundance of unexplored rock in the United States is geologically favorable for the occurrence of petroleum. Thus, there is no apparent imminent shortage of undiscovered petroleum; the only possible danger is that the industry's efficiency in locating new pools might fall below the limit of profitability. This possibility is best examined in the light of the recent record.

Drilling for petroleum has expanded greatly since World War II. Total footage drilled has reached a level more than double the prewar level (fig. 3). Exploratory drilling increased enormously—to a level about six times as great as the prewar level (fig. 3). In spite of this great expansion, very satisfactory success ratios have been maintained, particularly in exploratory holes (fig. 4). This record speaks for itself, and shows no present cause for alarm as to the industry's ability to locate new pools.

Some investigators (for example, Pogue and Hill, 1956, p. 19, and fig. 7*C*) have pointed to the increasing proportion of dry holes during the period since 1937 as an alarming trend. But such a trend is inevitable with great expansion in the proportion of the more hazardous exploratory drilling (fig. 3); moreover, the trend toward wider spacing of development wells tends to decrease their success ratio, for the same number of dry development wells must be drilled to determine the limits of a pool whether it is densely or sparsely drilled.

PETROLEUM PRODUCING CAPACITY IN THE FUTURE

Predictions of future trends are best guided by historical trends, and for a dynamic industry such as the petroleum industry, the most recent pertinent statistics should be the most meaningful in regard to the immediate future. This study has examined the several quantities or estimates upon which predictions as to future producibility have been based; and the conclusion therefrom is that the estimates of producing capacity are intrinsically the most accurate and most responsive to recent trends. Accordingly, the suggestion is made that the recent record of increase in producing capacity is the most reliable guide as to what may be expected in the foreseeable future.

Future petroleum-producing capacity of the United States will be controlled principally by the rate of completion of new producing

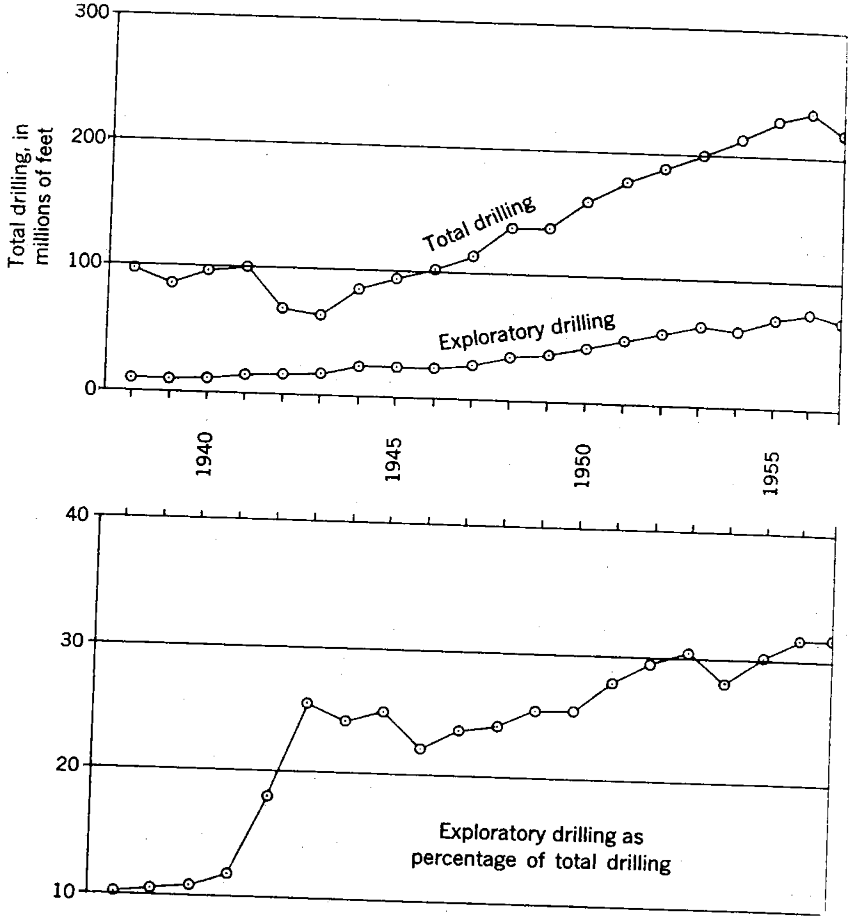

FIGURE 3.—Increase in drilling for oil and gas in the United States in the last 20 years. (Total drilling data from "World Oil," v. 148, no. 3, Feb. 15, 1959, p. 93; exploratory drilling data from Blanpied, 1959, p. 1130–1131.)

wells, which will in turn be controlled by the rate of drilling in search of production and the degree of success of such drilling. The drilling success will depend upon the quality of technical advice in locating and testing new wells, and upon the extent of reliance on such technical advice. It may be confidently assumed that the science of petroleum geology will continue to advance as more information becomes available, and that the industry will continue to rely largely on technical advice in drilling.

Producing capacity is also controlled in part by the extent of application of improvements in production techniques that tend to arrest the rate of production decline in most wells and to rejuvenate many wells. It may be confidently assumed that engineering advances will continue to be made in the future and that their application will continue to become more widespread.

Factors which could control future producing capacity, and which can best be appraised from a geologic viewpoint are (a) the existence of undiscovered petroleum accumulations sufficient to meet the requirements of expectable increase in production and producing capacity, and (b) the ability of the petroleum industry to discover and

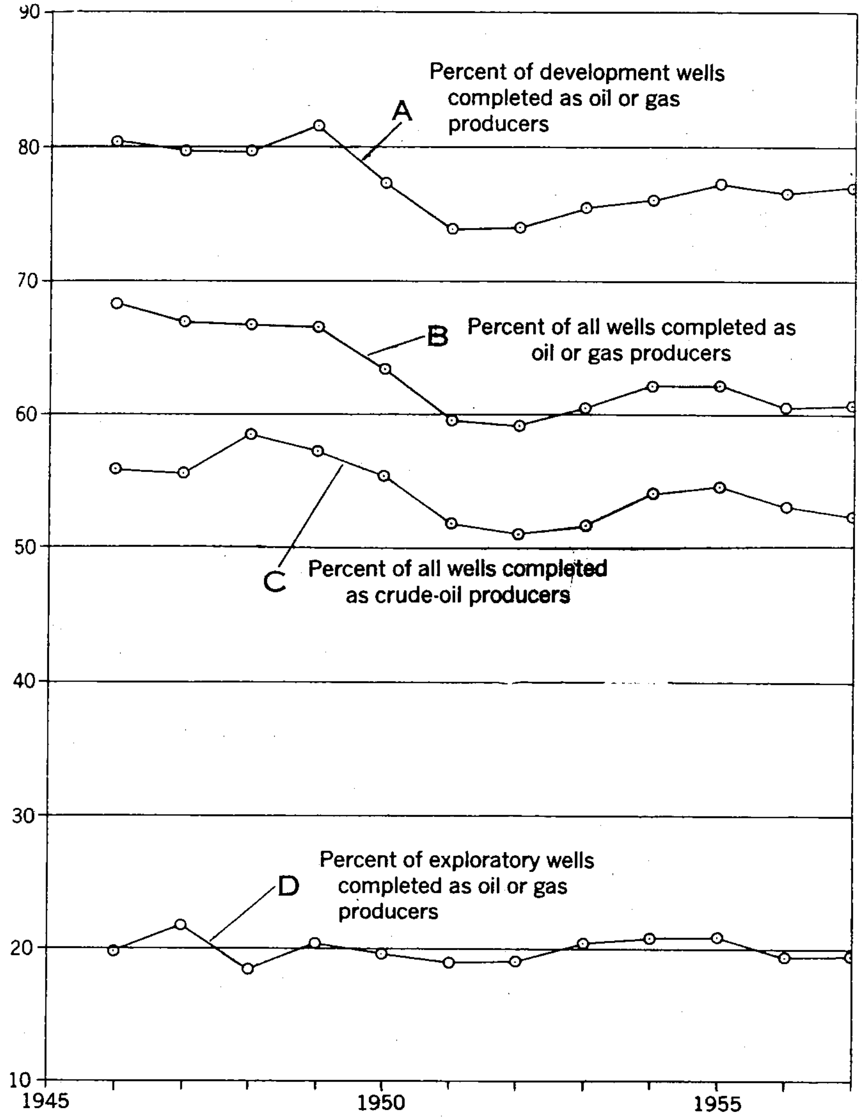

FIGURE 4.—Success ratios of wells drilled in search of production in the United States since World War II. (Data from "World Oil," v. 148, no. 3, Feb. 15, 1959, p. 93, and Blanpied, 1959, p. 1131.)

develop these accumulations at the rate required and under permissive economic conditions. These two factors have been considered in the foregoing sections of this report, and it was concluded that neither constitutes a limiting factor on expectable increase of producing capacity during the next 10–20 years at least.

The post-World War II record of increase in producing capacity and in reserve producing capacity is summarized graphically in figure 5*A*. Figure 5*B* shows the increase in total drilling in search of production and in completion of new crude-oil wells during the same period. Economic recession and a sharp increase in the quantity of imported crude oil and crude-oil products since 1956 resulted in a decrease in domestic production and a consequent decrease in drilling effort. But with the recent imposition of Federal controls on imports, and with the national economy again expanding, a resumption of the upward trends in production and drilling is likely. If economic incentives are such that the amount of drilling expands in the next 10–20 years at a rate comparable to the post-World War II expansion, an increase in crude-oil producing capacity comparable to that of the recent past may be expected. In view of the existence of considerable reserve capacity, probable continuation of petroleum imports, and probable slightly slower rate of increase in demand for crude oil, it seems likely that the amount of drilling will increase at a somewhat slower rate in the future. This would result, of course, in a somewhat slower rate of increase in producing capacity.

Available information on producing capacity does not permit determination of what proportion of the capacity generated by the completion of new wells is required to offset decline in capacity of old wells. It is suggested that more frequent and more detailed surveys of producing capacity would provide the most useful data for current and continuing analysis of the Nation's resource position with respect to petroleum: specifically, yearly surveys reporting separately (a) the capacity of wells that existed at the time of the previous survey, and (b) the capacity of new wells completed during the year. Such data would show the average rate of decline in capacity of older wells and would permit analysis of the amount of new capacity generated in relation to the drilling effort expended. Significant and persistent decrease in the quantity obtained by this analysis over a period of years would be the earliest sure warning that the upper limit of producing capacity was being approached.

The actual capacity of existing wells to produce natural gas and natural gas liquids has not been surveyed, but it doubtless exceeds present production levels by a much greater margin than the capacity to produce crude oil. This is evident from the statistics of proved-reserve estimates (table 2). Although these estimates do not reflect

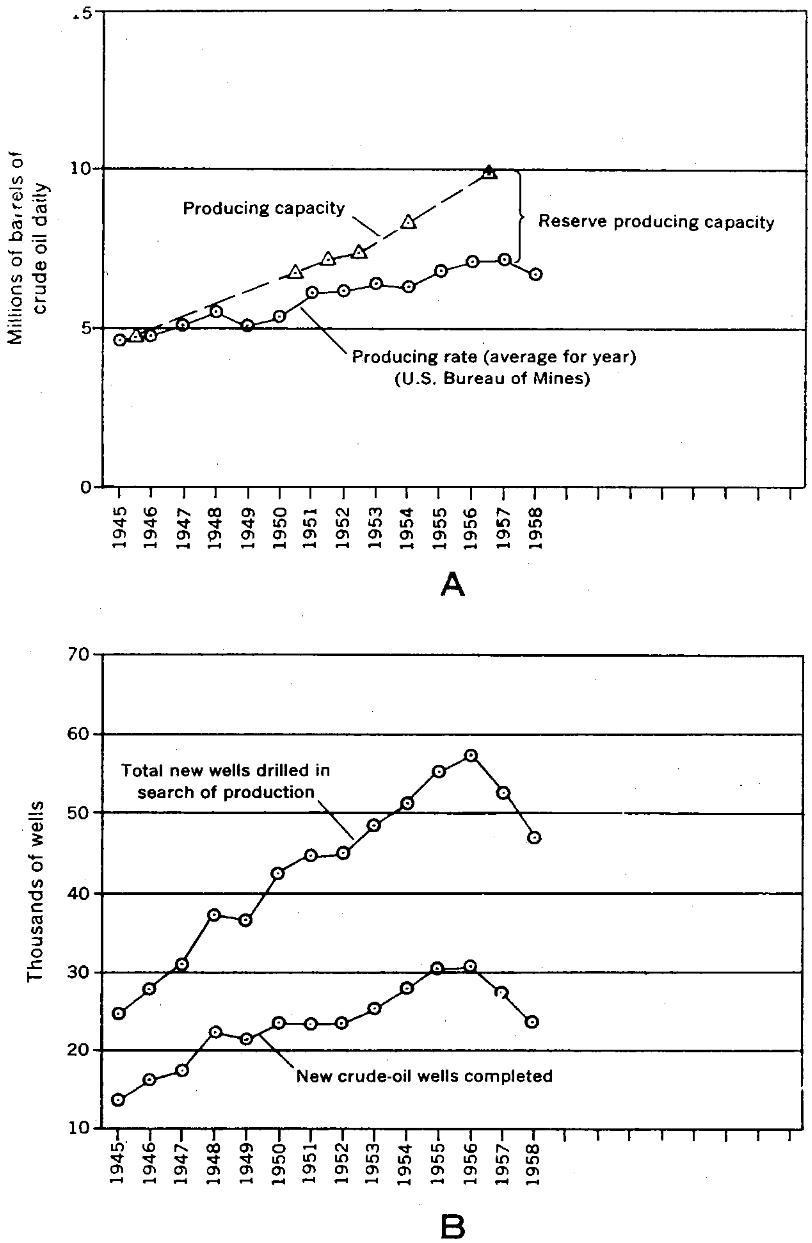

FIGURE 5.—*A*. Increase in crude-oil producing capacity (see table 1) and reserve producing capacity in the United States since World War II. *B*. Increase in total wells drilled in search of production and in new crude-oil wells completed in the United States since World War II. (Data from "World Oil," v. 148, no. 3, Feb. 15, 1959, p. 93.)

the total quantities producible from existing wells nor the rate at which they can be produced, they provide a measure of the approximate proportions of the several commodities so producible, for the estimates are computed on the same general basis. The most recent estimates indicate that there are more than 8,000 cubic feet of natural gas producible from known reservoirs for each barrel of producible crude oil. Recent production statistics, on the other hand, show that less than 4,000 cubic feet (net) of natural gas are produced per barrel of crude oil produced. Thus producible quantities are much greater, relative to production rates, for natural gas than for crude oil. And it may be safely assumed that gas reserves can, on the average, be produced at least as rapidly as crude oil. Gas associated with oil in the reservoir must generally be withdrawn at very restricted rates in order not to impair the ultimate recovery of oil, but most gas not associated with oil ("nonassociated" gas)—which constitutes about two-thirds of the total—may be extracted much more rapidly than oil without deleterious effect. Hence reserve-producing capacity for natural gas from wells must be relatively much greater than for crude oil. The effective producing capacity for natural gas is, of course, the capacity of existing pipelines to transport the gas, and is much smaller than the capacity of all wells.

The proved-reserve and production statistics similarly indicate a higher ratio of proved reserves to production for natural gas liquids than for crude oil. Moreover, unknown quantities of such liquids are available from wells but are not included in proved-reserve estimates because plants to process them did not exist or were not planned at the time of the estimate. Hence the surplus availability of natural gas liquids from existing wells is probably also relatively greater than for crude oil.

Production of natural gas and natural gas liquids has been increasing at a somewhat faster rate than production of crude oil, but, at the same time, increasingly greater relative quantities of natural gas and natural gas liquids are being discovered as the average depth of exploration increases. Moreover, the expanding market for natural gas and natural gas liquids has resulted in more and more deliberate exploration for those commodities. It may be expected that there will continue to be relatively greater availability of natural gas and natural gas liquids for many years to come.

CONCLUSIONS

1. From study of the nature and probable accuracy of the several types of quantitative data and estimates that have been used as bases for predicting future petroleum producing capacity of the United States, it is concluded that the recent rate of growth in producing capacity itself is the most realistic basis.

2. From consideration of the large volume of geologically favorable rocks yet to be explored in the United States, and the recent record of success in exploring geologically similar rocks, it is concluded that the quantity of undiscovered petroleum will not constitute a limiting factor on increase of producing capacity in the next 10–20 years at least, and probably for a much longer time.
3. The rate of increase in producing capacity is governed primarily by the rate of completion of new wells. If economic incentives in the domestic petroleum industry in the next 10–20 years justify an expansion in drilling effort comparable to the 1945–58 expansion, a further increase in crude-oil producing capacity, comparable to that of the recent past, may be expected.
4. The outlook for future domestic supply of natural gas and natural gas liquids is even more favorable than for crude oil.

REPORTS ON PROVED RESERVES

Excerpts from "Reports on Proved Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada," v. 13, Dec. 31, 1958, published jointly by American Gas Association (p. 15–16), American Petroleum Institute (p. 5–7), and Canadian Petroleum Association:

"Report of the American Petroleum Institute's Committee on Petroleum Reserves"

The estimates in this report, as in all previous annual reports of this committee, refer solely to proved or blocked-out reserves. They include only oil and natural gas liquids recoverable under existing economic and operating conditions.

The estimates made for this report by your committe do not include:

1. Oil* under the unproved portions of partly developed fields.
2. Oil in untested prospects.
3. Oil that may be present in unknown prospects in regions believed to be generally favorable.
4. Oil that may become available by fluid injection methods from fields where such methods have not yet been applied.
5. Oil that may become available through processing of natural gas.
6. Oil that can be made from oil shale, coal, or other substitute sources.

In the case of new discoveries, both of new fields and of new pools (pays, reservoirs) in old fields, which are seldom fully developed in the first year and in fact for several years thereafter, the estimates of proved reserves necessarily represent but a part of the reserves which may ultimately be assigned to the new reservoirs discovered each year. For a one-well field, where development has not yet gone beyond the discovery well, the area assigned as proved is usually small in regions of complex geological conditions but may be larger where the geology is relatively simple. In a sparsely drilled pool the area between wells is considered to be proved only if the geological and engineering

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*The word "oil," unless defined as crude oil, is used in this report as equivalent to liquid hydrocarbons.

data assure that such area will produce when drilled. The total of new oil through discoveries estimated as proved in each year is comparatively small, because development is usually not extensive during the first year. The total of new oil through extensions, on the other hand, is comparatively large. As knowledge of the factors affecting production and reservoir performance becomes available, and as these factors are studied, reserves in older fields can be estimated with greater precision and revised accordingly. Therefore, the total quantity of the new proved reserves for the year includes the oil from discoveries and extensions, modified by revisions of previous estimates where new data have made better information available.

Proved reserves are both drilled and undrilled. The proved drilled reserves, in any pool, include the oil estimated to be recoverable by the production systems now in operation, whether with or without fluid injection, and from the area actually drilled up on the spacing pattern in effect in that pool. The proved undrilled reserves, in any pool, include reserves under undrilled spacing units which are so close, and so related, to the drilled units that there is every reasonable probability that they will produce when drilled.

This committee uses the term "fluid injection" to include (1) what is commonly called "pressure maintenance"; (2) cycling; and (3) secondary recovery in its original sense, namely, fluid injection applied relatively late in the development history of a reservoir (pool) with the purpose of stimulating petroleum production after recovery by primary methods of flowing or artificial lift has approached an economic limit. The reserves which may become available as a result of fluid injection are regarded as *proved only* after thorough testing by a pilot plant, or after operations of an installed fluid injection procedure has confirmed the anticipation of increased recovery.

The committee again wishes especially to stress the fact that its estimates of proved reserves cannot be used in measuring the rate at which these reserves can be produced with or without physical waste. Oil cannot be produced from the permeable rocks in which it occurs at any desired rate, because the flow of oil through the pores of the oil-bearing rocks is definitely controlled by the physical factors of the reservoir. As a matter of fact, today's known oil can be recovered only over a period of many years and at gradually declining annual rates. This has been widely demonstrated by past performance under all kinds of operating conditions. Therefore, only incorrect conclusions as to the life of these reserves can be obtained by dividing these reserves by the current rate of production.

"Report of the Committee on Natural Gas Reserves of the American Gas Association."

"The Committee wishes to point out that it is often not possible to estimate the total reserves of a field in the year of its discovery. Satisfactory estimates can be made only after there has been sufficient drilling in the fields and, in some cases, adequate production history established. For these reasons, the reserves listed as discovered during any current year must be considered only as the reserves indicated by the drilling in that year. The reserves of all fields and pools are reviewed and revised upward or downward in each succeeding annual report to reflect additional information on preceding estimates. These changes are shown as "Extensions and Revisions."

The procedure followed in estimating and assembling the proved reserves figures is the same as that used in the past reports. A proved reserve may be in either the drilled or undrilled portion of a given field. When the undrilled area is considered proved, it is so related to the developed acreage and the known field geology and structure that its productive ability is considered assured. Proved recoverable reserves of natural gas are those reserves estimated to be producible under present operating practices, with no consideration being given to their ultimate use. Since the estimates are made by pools, the recovery factors or abandonment pressures used in the calculations are governed by the operating conditions in each individual pool. Proved recoverable reserves of natural gas liquids are those contained in the recoverable gas reserves subject to being produced as natural gas liquids by separators or extraction plants, now in operation, under construction or planned for the immediate future. For purposes of developing reserves estimates, natural gas liquids are defined as those hydrocarbon liquids which are gaseous or in solution with crude oil in the reservoir and which are recoverable as liquids by the processes of condensation or absorption which take place in field separators, scrubbers, gasoline plants, or cycling plants. Natural gasoline, condensate, and liquified petroleum gases fall in this category. While the liquids so collected and the products derived from them in some of the modern plants are known by a variety of names, they have been grouped together here under the general heading "Natural Gas Liquids."

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